

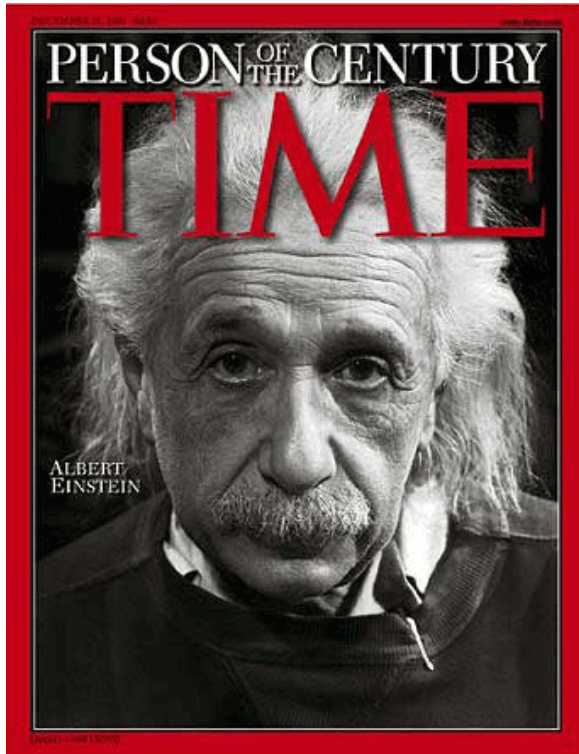
The echo of Einstein's greatest blunder

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Outline

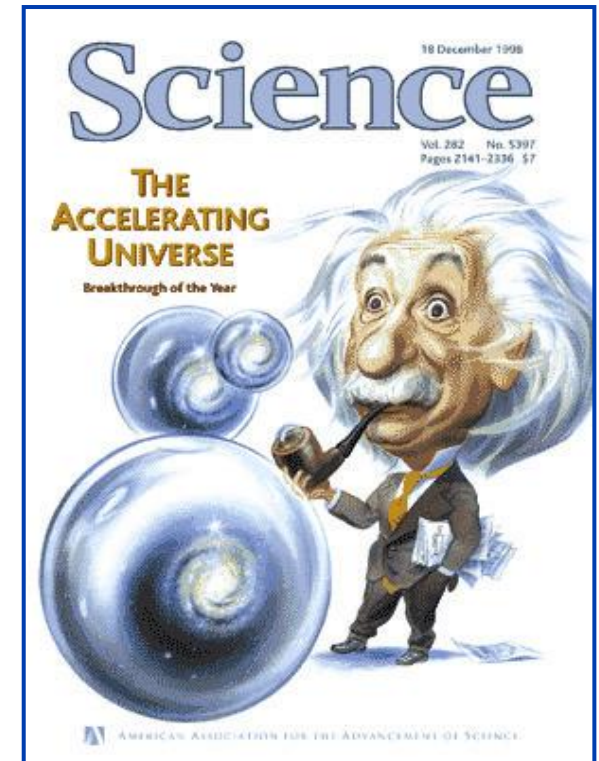
- Dark energy and standard rulers.
- Cosmic sound: baryon acoustic oscillations.
- Theoretical issues.
- Modeling issues.
- Prospects and conclusions.

Beyond Einstein?



1919

Our theories of the Universe are based upon General Relativity which, like Newton's theory, predicts that gravity is an attractive force which would act to slow any existing expansion.



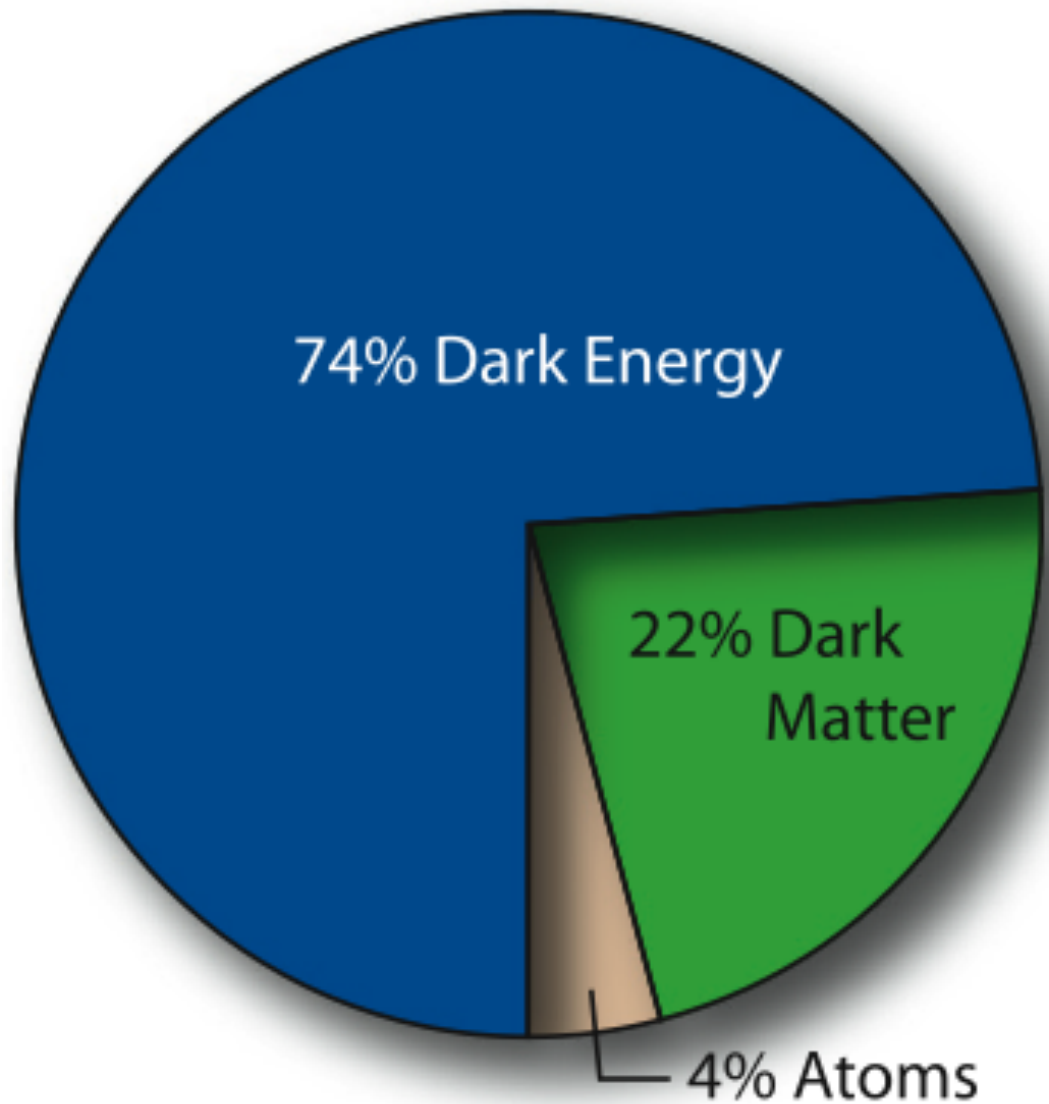
1998

The discovery that the expansion of the Universe is currently accelerating was heralded as the "Breakthrough of the year" by *Science* in 1998.

Dark energy

- There are now several independent ways to show that the expansion of the Universe is accelerating.
- This indicates that:
 - a) Our theory of gravity (General Relativity) is wrong.
 - b) The universe is dominated by a material which violates the strong energy condition: $\rho + 3p > 0$.
- If (b) then it cannot be any “classical” fluid, but some weird “quantum stuff” which dominates the energy density of the Universe (today). We refer to it as “dark energy”.
- The most prosaic explanation is Einstein’s cosmological constant, which can be interpreted as the energy of empty space.

Dark energy domination



The dynamics of the Universe are dominated by dark matter -- about which we know an awful lot except what it is -- and dark energy about which we know almost nothing.

If in doubt, make more/different measurements!

Dark energy equation of state

- The amount of dark energy is actually quite well constrained by present data:

$$\rho_{\text{DE}} = (1.43 \pm 0.09) \times 10^{-29} \text{ g/cm}^3$$

- What distinguishes models is the time-evolution of ρ_{DE}
- This is usually described by the equation of state: $w=p/\rho$.
 - A cosmological constant, vacuum energy, has $w=-1$.
 - Many (most) dark energy models have $w>-1$, and time evolving.
- So the “holy grail” of DE research is to demonstrate that $w \neq -1$ at any epoch.

Probing DE via cosmology

- We “see” dark energy through its effects on the expansion of the universe:

$$H^2(z) = \frac{8\pi G}{3} \sum_i \rho_i(z)$$

- Three (3) main approaches
 - Standard candles
 - measure d_L (integral of H^{-1})
 - Standard rulers
 - measure d_A (integral of H^{-1}) and $H(z)$
 - Growth of fluctuations.
 - Crucial for testing extra ρ components vs modified gravity.

Standard rulers

- Suppose we had an object whose length (in *meters*) we knew as a function of cosmic epoch.
- By measuring the angle ($\Delta\theta$) subtended by this ruler ($\Delta\chi$) as a function of redshift we map out the angular diameter distance d_A

$$\Delta\theta = \frac{\Delta\chi}{d_A(z)} \quad d_A(z) = \frac{d_L(z)}{(1+z)^2} \propto \int_0^z \frac{dz'}{H(z')}$$

- By measuring the redshift interval (Δz) associated with this distance we map out the Hubble parameter $H(z)$

$$c\Delta z = H(z) \Delta\chi$$

Ideal properties of the ruler?

To get competitive constraints on dark energy we need to be able to see changes in $H(z)$ at the 1% level -- this would give us “statistical” errors in DE equation of state ($w=p/\rho$) of $\sim 10\%$.

- We need to be able to calibrate the ruler accurately over most of the age of the universe.
- We need to be able to measure the ruler over much of the volume of the universe.
- We need to be able to make ultra-precise measurements of the ruler.

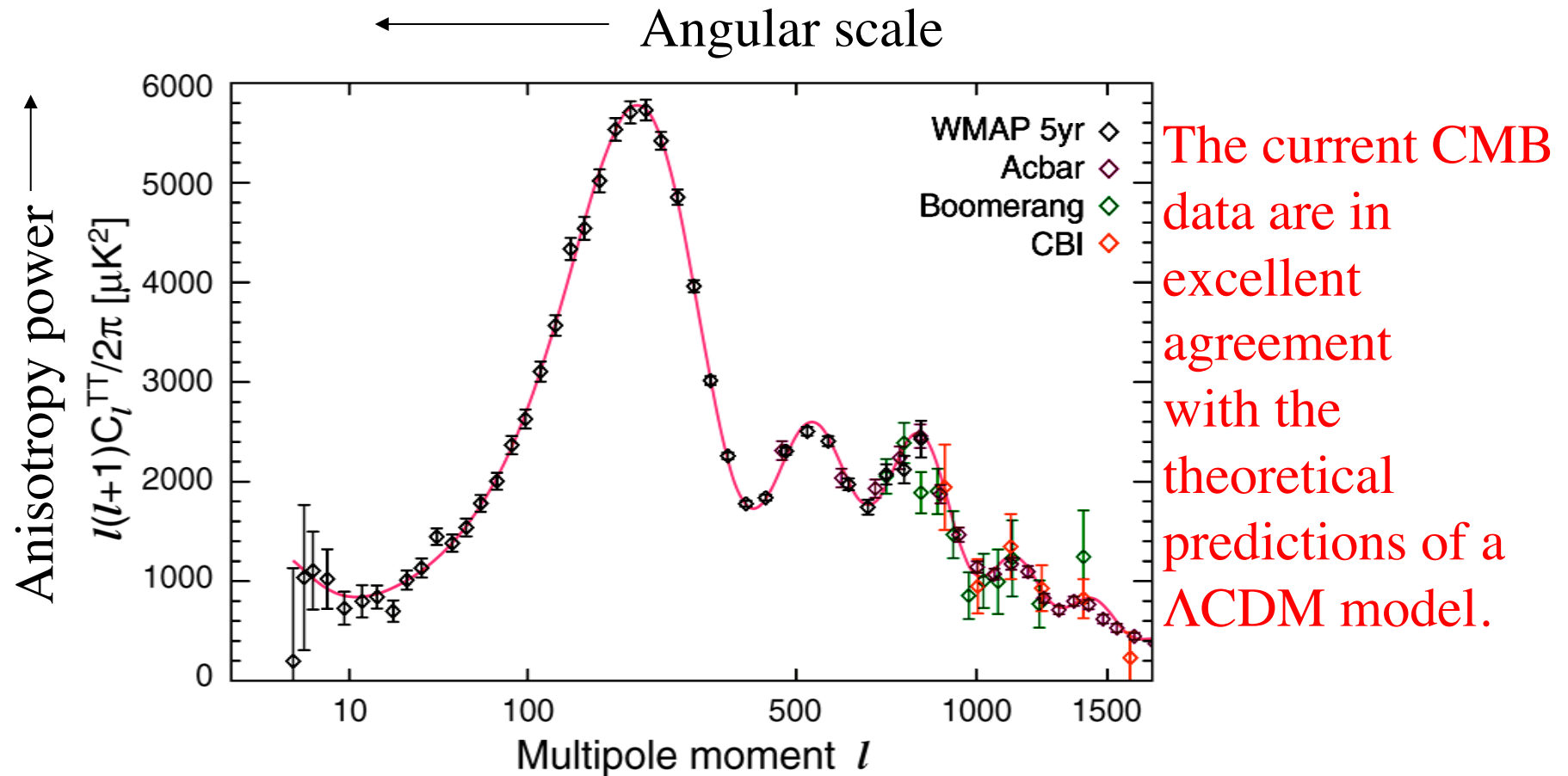
Where do we find such a ruler?

- Cosmological objects can probably never be uniform enough.
- We believe that the laws of physics haven't changed over the relevant time scales.
 - Use features arising from physical processes in the early Universe.
- Use statistics of the large-scale distribution of matter and radiation.
 - If we work on large scales or early times perturbative treatment is valid and calculations under control.

Sunyaev & Zel'dovich (1970); Peebles & Yu (1970); Doroshkevitch, Sunyaev & Zel'dovich (1978); ...; Hu & White (1996); Cooray, Hu, Huterer & Joffe (2001); **Eisenstein** (2003); Seo & Eisenstein (2003); Blake & Glazebrook (2003); Hu & Haiman (2003); ...

Back to the beginning ...

The CMB power spectrum



Hinshaw et al. (2008)

The cartoon

- At early times the universe was hot, dense and ionized. Photons and matter were tightly coupled by Thomson scattering.
 - Short m.f.p. allows fluid approximation.
- Initial fluctuations in density and gravitational potential drive acoustic waves in the fluid: compressions and rarefactions with $\delta_\gamma \propto \delta_b$.
- Consider a (standing) plane wave perturbation of comoving wavenumber k .
- If we expand the Euler equation to first order in the Compton mean free path over the wavelength we obtain a driven harmonic oscillator:

$$\frac{d}{d\tau} \left[m_{\text{eff}} \frac{d\delta_b}{d\tau} \right] + \frac{k^2}{3} \delta_b = F[\Psi] \quad m_{\text{eff}} = 1 + 3\rho_b/4\rho_\gamma$$

The cartoon

- These perturbations show up as temperature fluctuations in the CMB.
- Since $\rho \sim T^4$ for a relativistic fluid the temperature perturbations look like:

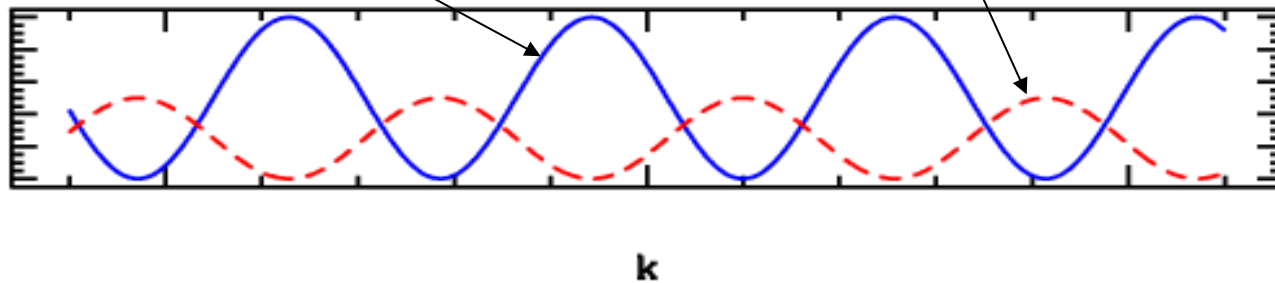
$$\Delta T \sim \delta \rho_\gamma^{1/4} \sim A(k) \cos(kc_s t) \quad [\text{harmonic wave}]$$

- ... plus a component due to the velocity of the fluid (the Doppler effect).

The cartoon

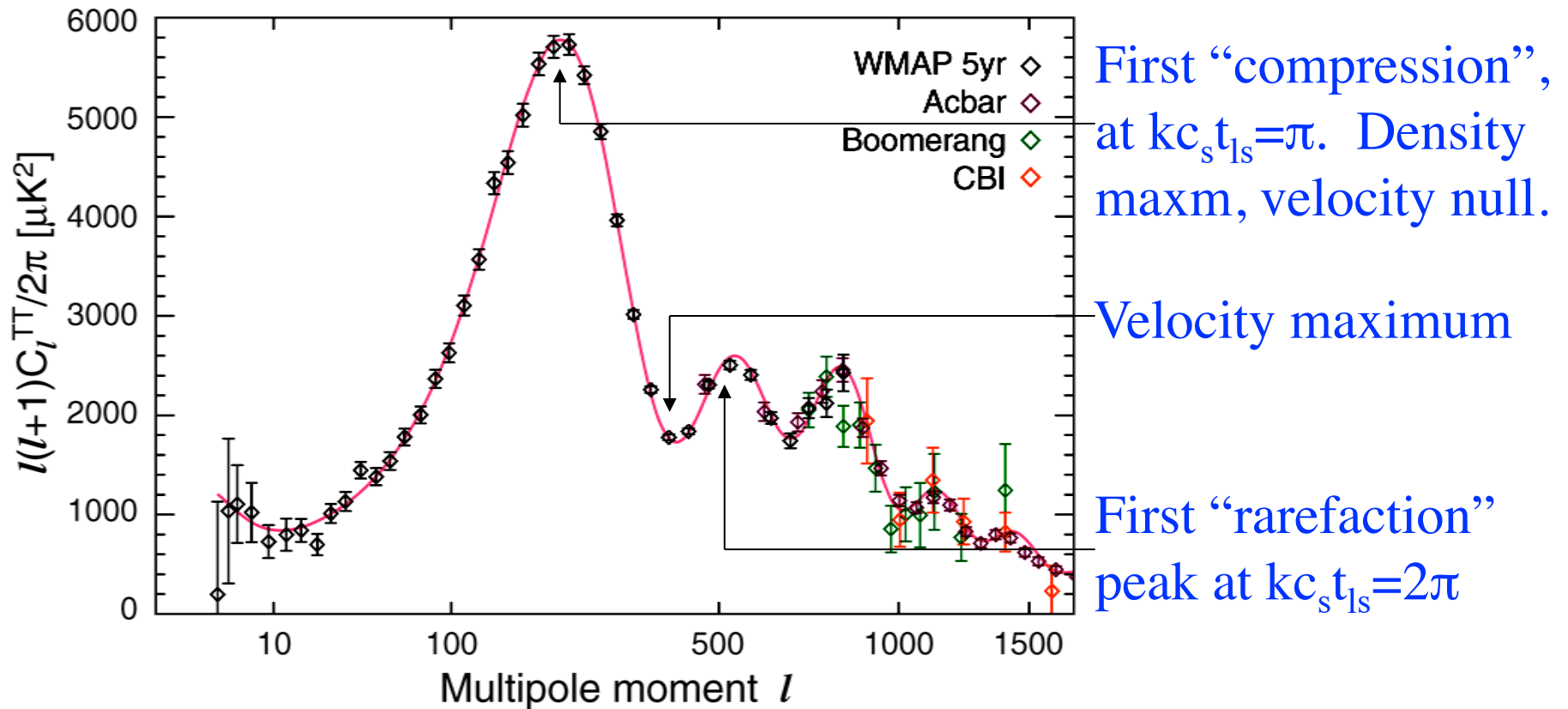
- A sudden “recombination” decouples the radiation and matter, giving us a snapshot of the fluid at “last scattering”.

$$(\Delta T)_{\text{ls}}^2 \sim \cos^2(kc_s t_{\text{ls}}) + \text{velocity terms}$$



- These fluctuations are then projected on the sky with $\lambda \sim r_{\text{ls}} \theta$ or $l \sim k r_{\text{ls}}$

Acoustic oscillations seen!



Acoustic scale is set by the *sound horizon* at last scattering: $s = c_s t_{ls}$

CMB calibration

- Not coincidentally the sound horizon is extremely well determined by the structure of the acoustic peaks in the CMB.

$$\begin{aligned}s &= 146.8 \pm 1.8 \text{ Mpc} && \text{WMAP 5}^{\text{th}} \text{ yr data} \\ &= (4.53 \pm 0.06) \times 10^{24} \text{ m}\end{aligned}$$

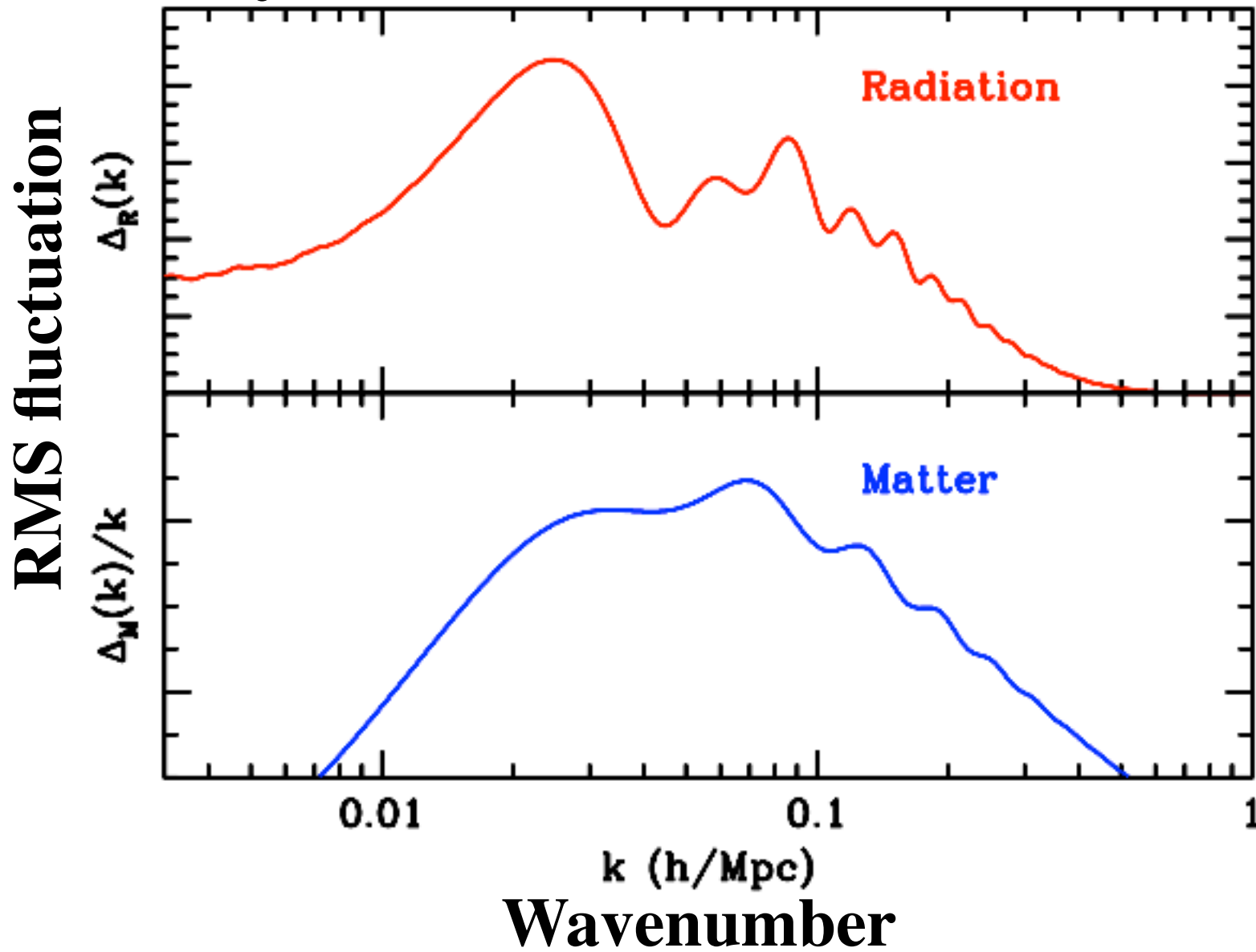


Dominated by uncertainty in ρ_m from poor constraints near 3rd peak in CMB spectrum.
(Planck will nail this!)

Baryon oscillations in $P(k)$

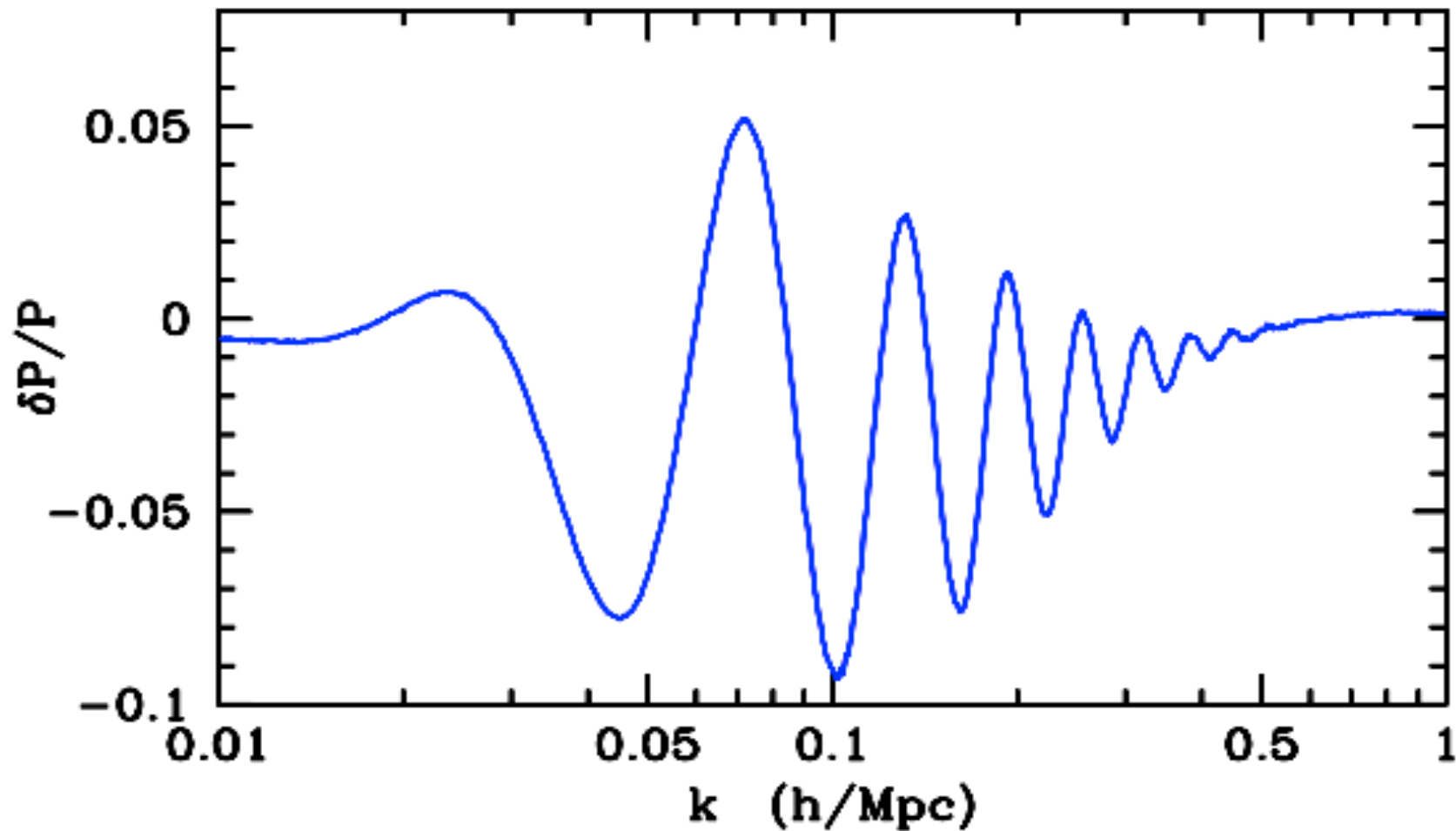
- Since the baryons contribute $\sim 15\%$ of the total matter density, the total gravitational potential is affected by the acoustic oscillations with scale set by s .
- This leads to small oscillations in the matter power spectrum $P(k)$.
 - No longer order unity, like in the CMB
 - Now suppressed by $\Omega_b/\Omega_m \sim 0.1$
- **Note:** all of the matter sees the acoustic oscillations, not just the baryons.

Baryon (acoustic) oscillations



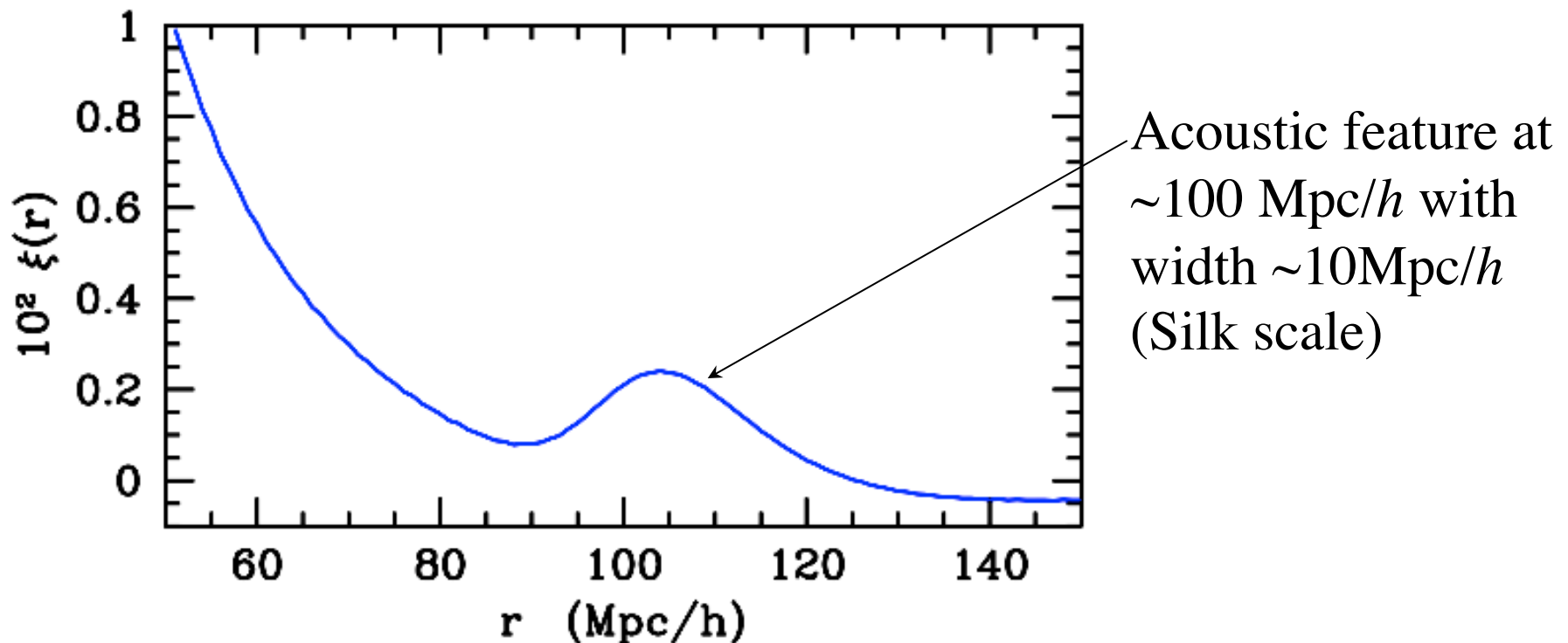
Divide out the gross trend ...

A damped, almost harmonic sequence of “wiggles” in the power spectrum of the mass perturbations of amplitude $O(10\%)$.



In configuration space

- The configuration space picture offers some important insights, and will be useful when we consider non-linearities and bias.
- In configuration space we measure not power spectra but correlation functions: $\xi(r) = \int P(k) e^{i\mathbf{k}\cdot\mathbf{r}} d^3k = \int \Delta^2(k) j_0(kr) d\ln k$.
- A harmonic sequence would be a δ -function in r , the shift in frequency and diffusion damping broaden the feature.



Configuration space

In configuration space one uses a Green's function method to solve the equations, rather than expanding k -mode by k -mode. (Bashinsky & Bertschinger 2000)

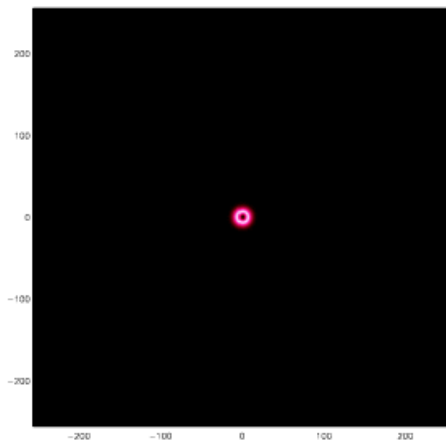
To linear order Einstein's equations look similar to Poisson's equation relating ϕ and δ , but upon closer inspection one finds that the equations are hyperbolic: they describe traveling waves.

[effects of local stress-energy conservation, causality, ...]

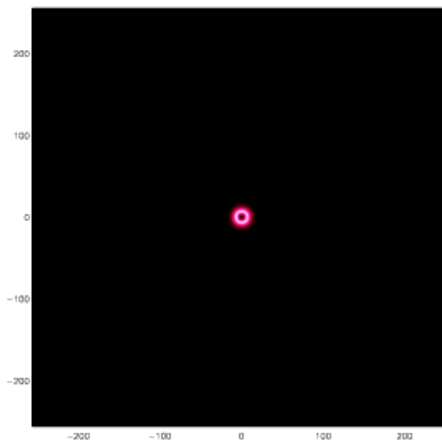
The acoustic wave

Start with a single perturbation. The plasma is totally uniform except for an excess of matter at the origin.

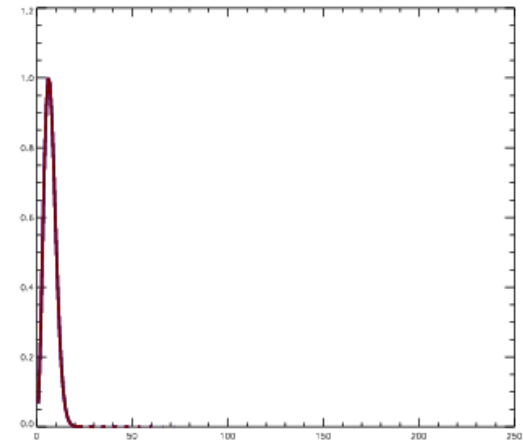
High pressure drives the gas+photon fluid outward at speeds approaching the speed of light.



Baryons



Photons

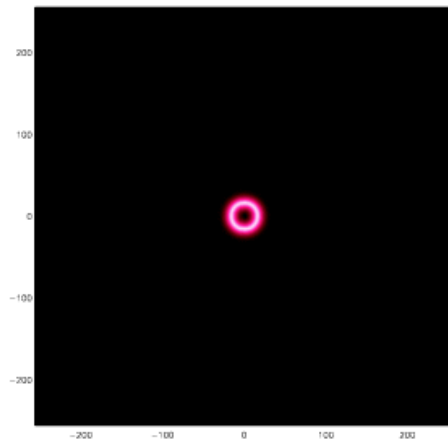


Mass profile

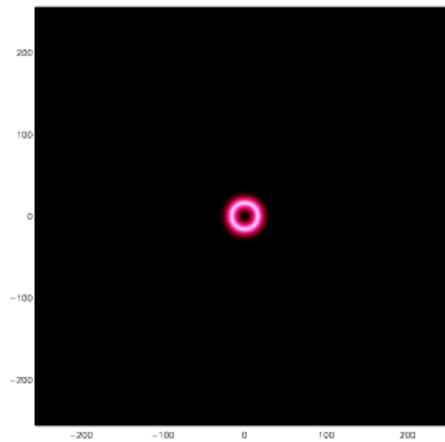
Eisenstein, Seo & White (2006)

The acoustic wave

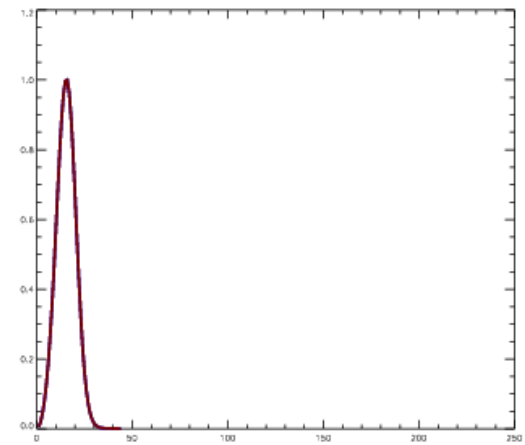
Initially both the photons and the baryons move outward together, the radius of the shell moving at over half the speed of light.



Baryons

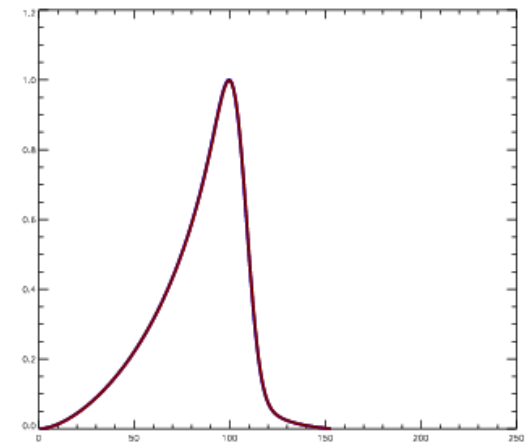
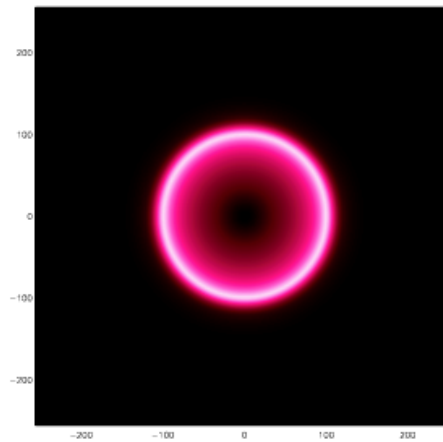
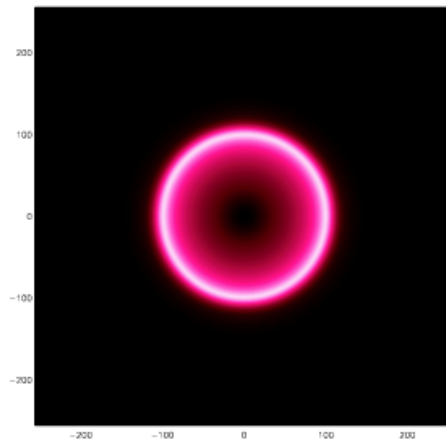


Photons



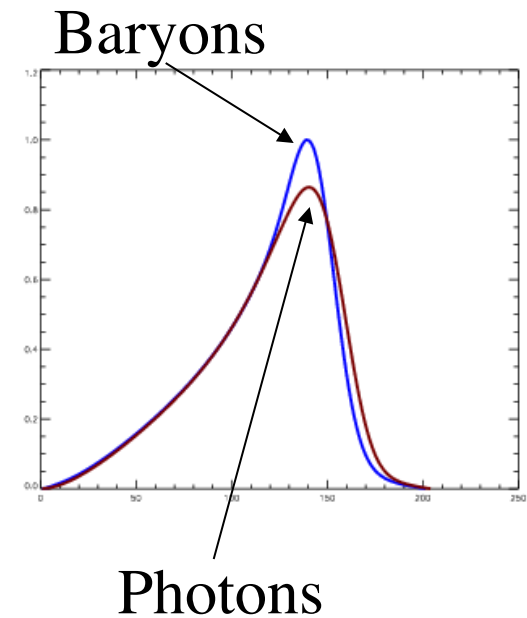
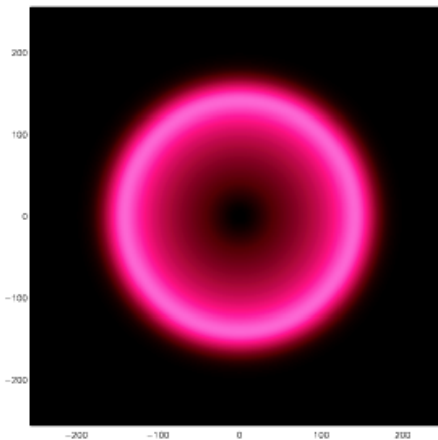
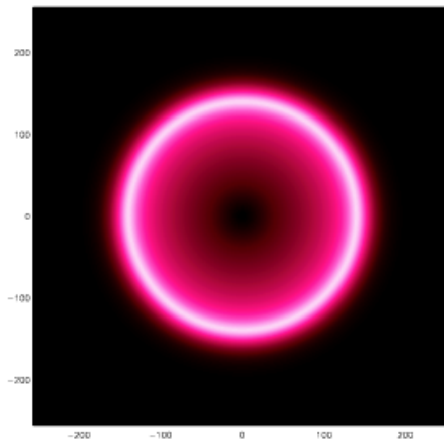
The acoustic wave

This expansion continues for 10^5 years



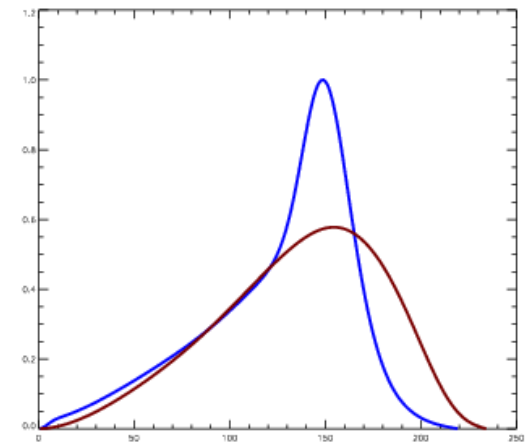
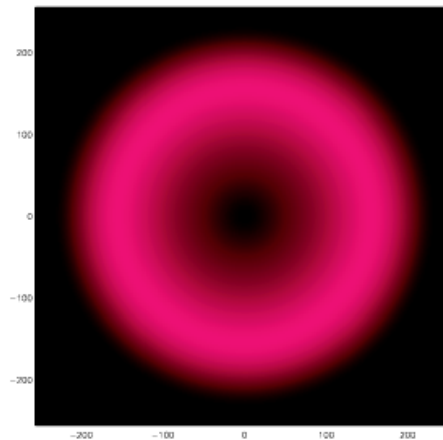
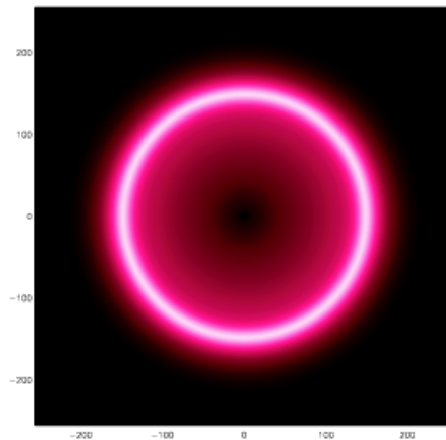
The acoustic wave

After 10^5 years the universe has cooled enough the protons capture the electrons to form neutral Hydrogen. This decouples the photons from the baryons. The former quickly stream away, leaving the baryon peak stalled.

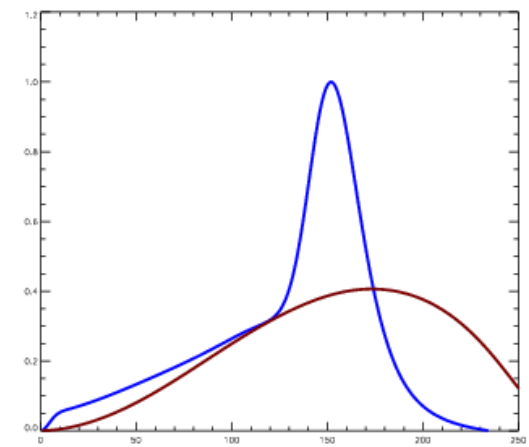
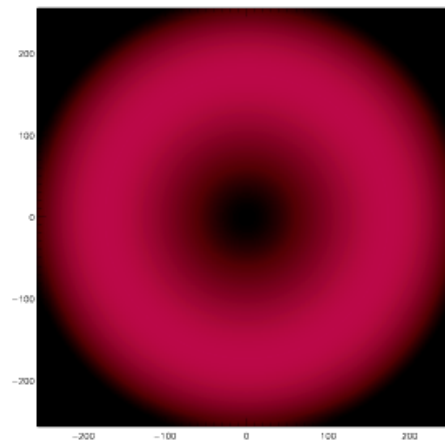
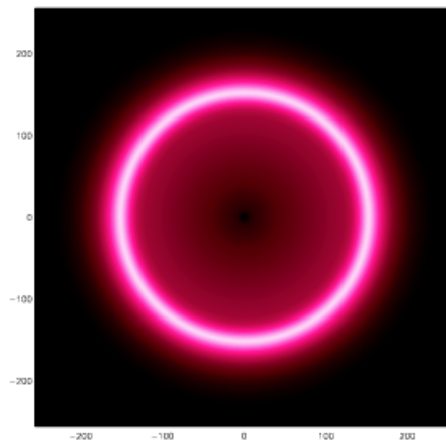


The acoustic wave

The photons continue to stream away while the baryons, having lost their motive pressure, remain in place.

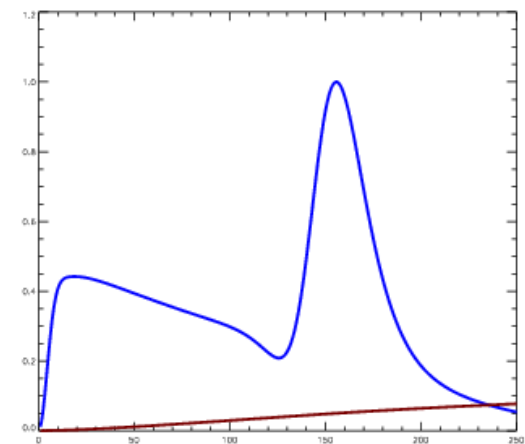
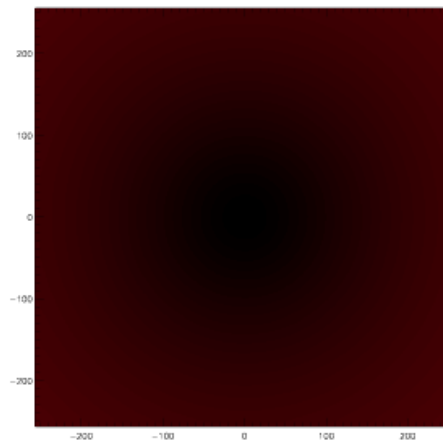
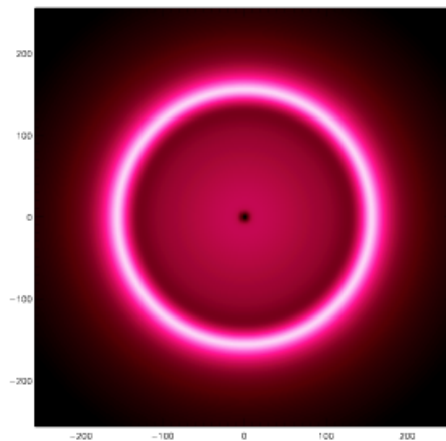


The acoustic wave



The acoustic wave

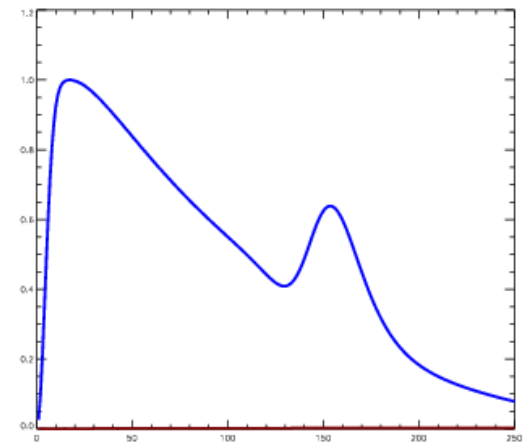
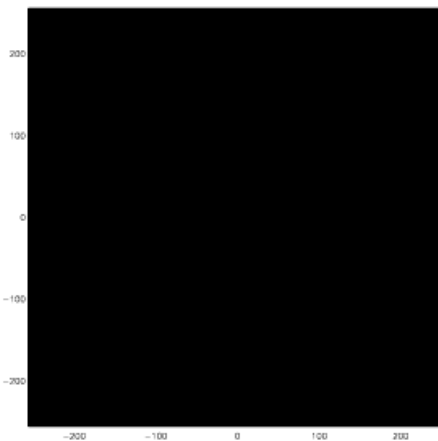
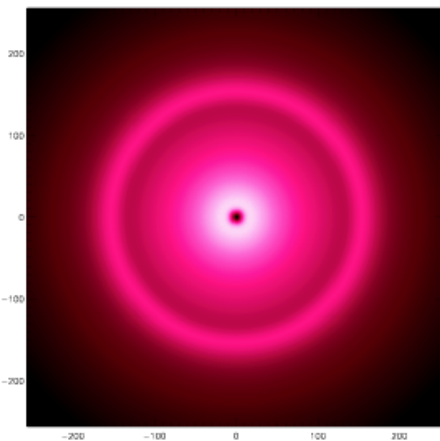
The photons have become almost completely uniform, but the baryons remain overdense in a shell 100Mpc in radius. In addition, the large gravitational potential well which we started with starts to draw material back into it.



The acoustic wave

As the perturbation grows by $\sim 10^3$ the baryons and DM reach equilibrium densities in the ratio Ω_b/Ω_m .

The final configuration is our original peak at the center (which we put in by hand) and an “echo” in a shell roughly 100Mpc in radius.



Further (non-linear) processing of the density field acts to broaden and very slightly shift the peak -- but galaxy formation is a local phenomenon with a length scale ~ 10 Mpc, so the action at $r=0$ and $r \sim 100$ Mpc are essentially decoupled. We will return to this ...

Features of baryon oscillations

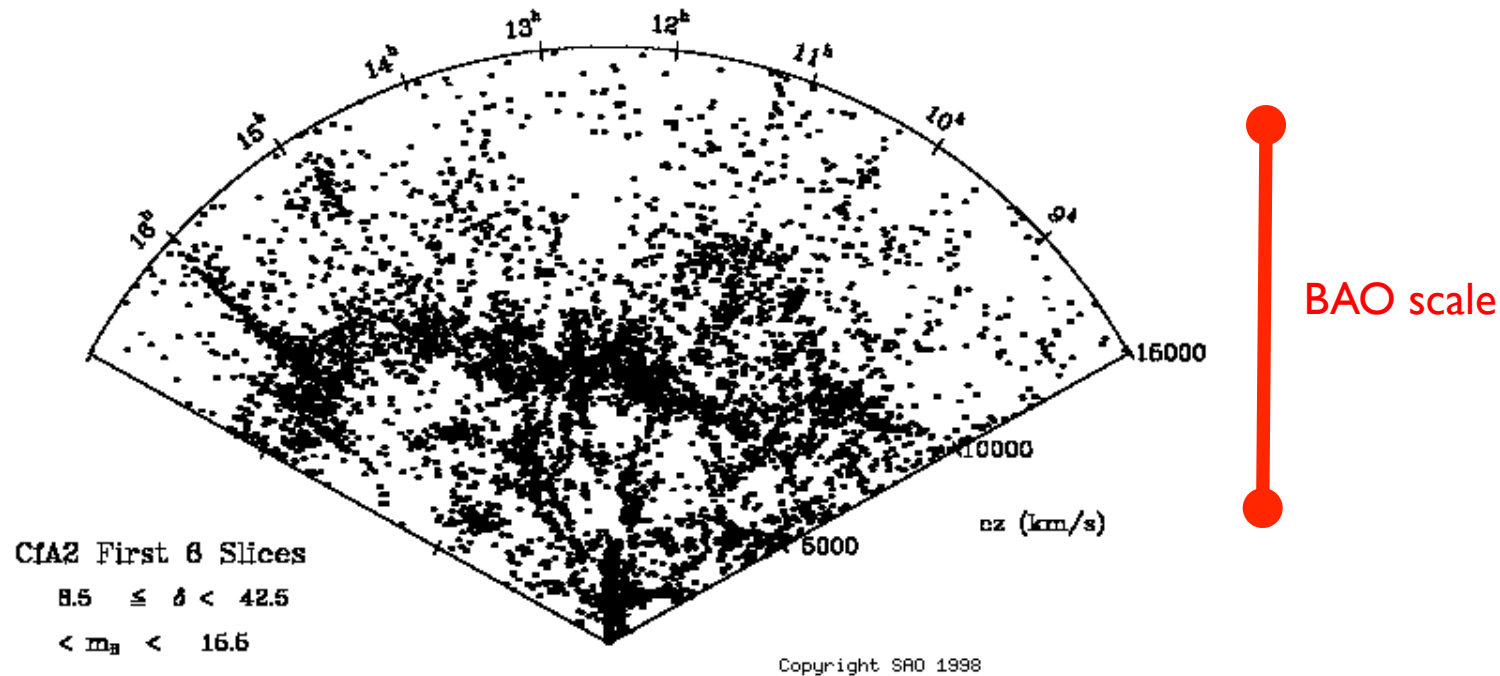
- Firm prediction of models with $\Omega_b > 0$
- Positions well predicted once (physical) matter and baryon density known - calibrated by the CMB.
- Oscillations are “sharp”, unlike other features of the power spectrum.
- Internal cross-check:
 - d_A should be the integral of $H^{-1}(z)$.
- Since have $d(z)$ for several z 's can check spatial flatness (addition law for distances).
- Ties low- z distance measures (e.g. SNe) to absolute scale defined by the CMB (in Mpc, not $h^{-1}\text{Mpc}$).
 - Allows $\sim 1\%$ measurement of h using trigonometry!

The program

- Find a tracer of the mass density field and compute its 2-point function.
- Locate the features in the above corresponding to the sound horizon, s .
- Measure the $\Delta\theta$ and Δz subtended by the sound horizon, s , at a variety of redshifts, z .
- Compare to the value at $z \sim 10^3$ to get d_A and $H(z)$
- Infer expansion history, DE properties, modified gravity.

But ruler inconveniently large ...

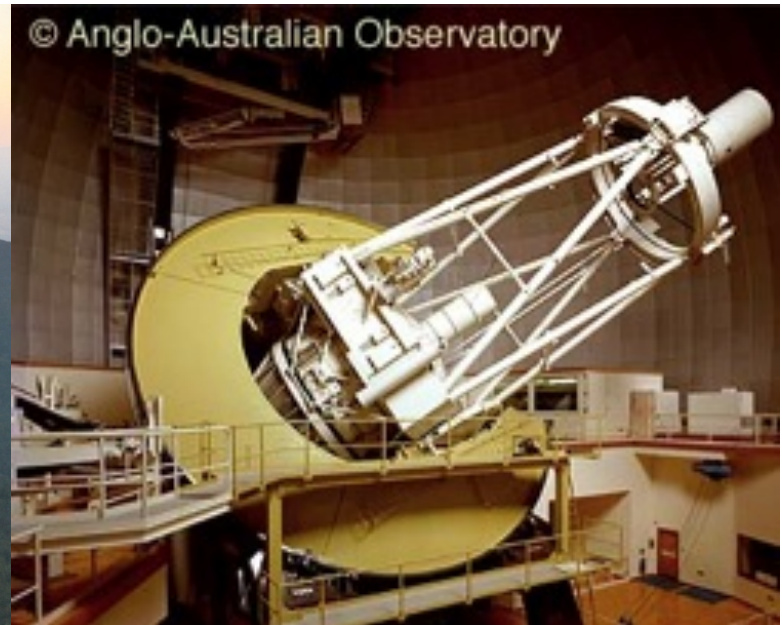
Early surveys too small



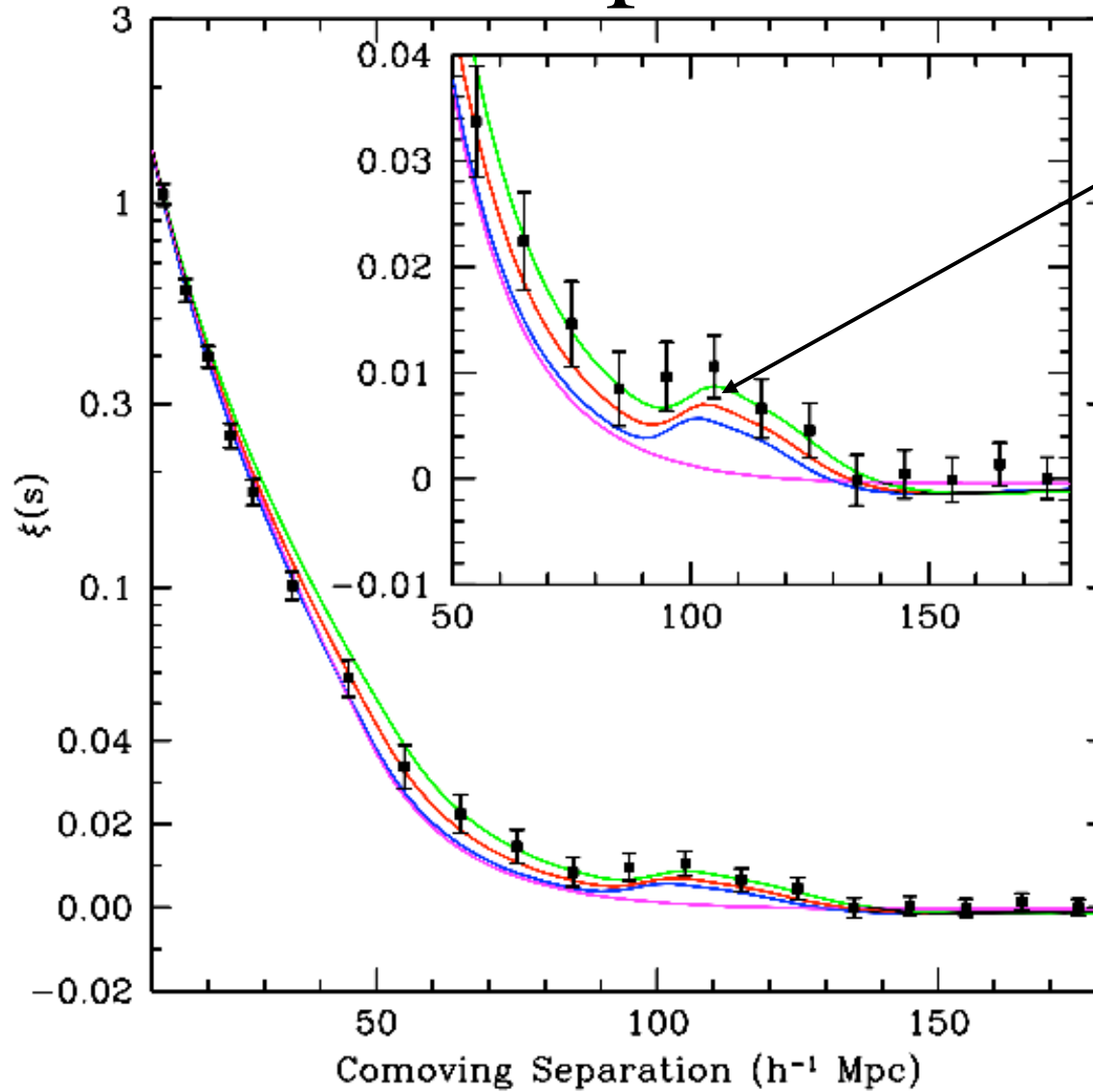
CfA2 redshift survey (Geller & Huchra 1989)
Formally, this could “measure” BAO with a $\sim 0.05\sigma$ detection

Finally technically possible

SDSS and 2dF surveys allow detection of BAO signal ...



Another prediction verified!!



Eisenstein et al. (2005)
detect oscillations in the
SDSS LRG $\xi(r)$ at $z \sim 0.35$!
Knowing s determines D
($z=0.35$).

About 10% of the way to
the surface of last
scattering!

Constraints argue for the
existence of DE, but do
not strongly constrain its
properties.

Current state of the art

1. Eisenstein et al 2005
 - o 3D map from SDSS
 - o 46,000 galaxies, $0.72 (h^{-1} \text{ Gpc})^3$

(spectro-z)
4% distance measure
2. Cole et al 2005
 - o 3D map from 2dFGRS at AAO
 - o 221,000 galaxies in $0.2 (h^{-1} \text{ Gpc})^3$

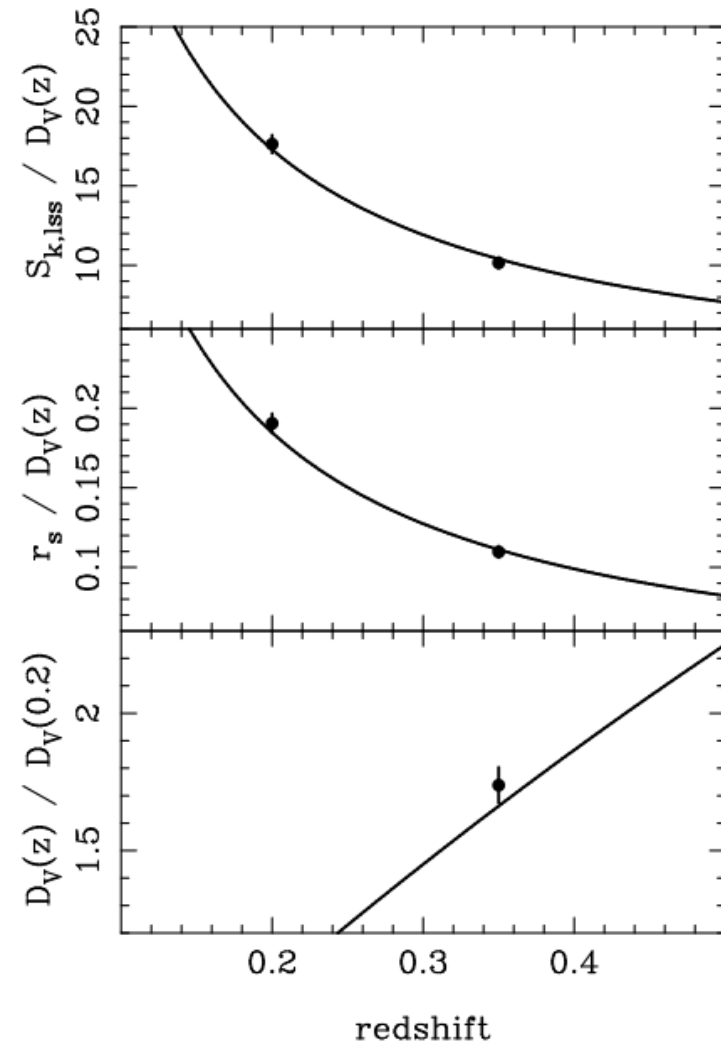
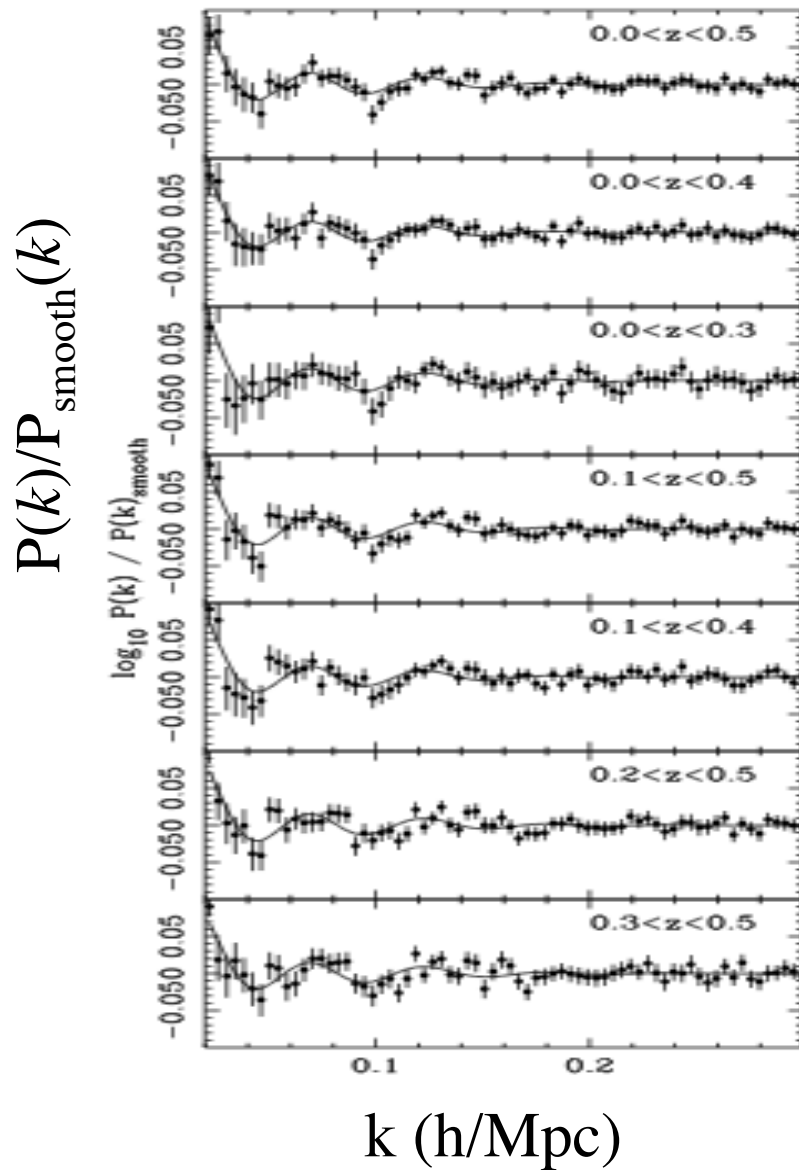
(spectro-z)
5% distance measure
3. Hutsi (2005ab)
 - o Same data as (1).
4. Padmanabhan et al 2007
 - o Set of 2D maps from SDSS
 - o 600,000 galaxies in $1.5 (h^{-1} \text{ Gpc})^3$

(photo-z)
6% distance measure
5. Blake et al 2007
 - o (Same data as above)
6. Percival et al 2007
 - o (Combination of SDSS+2dF)
7. Okumura et al 2007
 - o (Anisotropic fits)
15. Gaztanaga et al. 2008a
 - o (3pt function)

(spectro-z)
Detection
16. Gaztanaga et al. 2008b
 - o (line-of-sight)
19. Percival et al. 2009
 - o (DR7)

(spectro-z)
2.7%

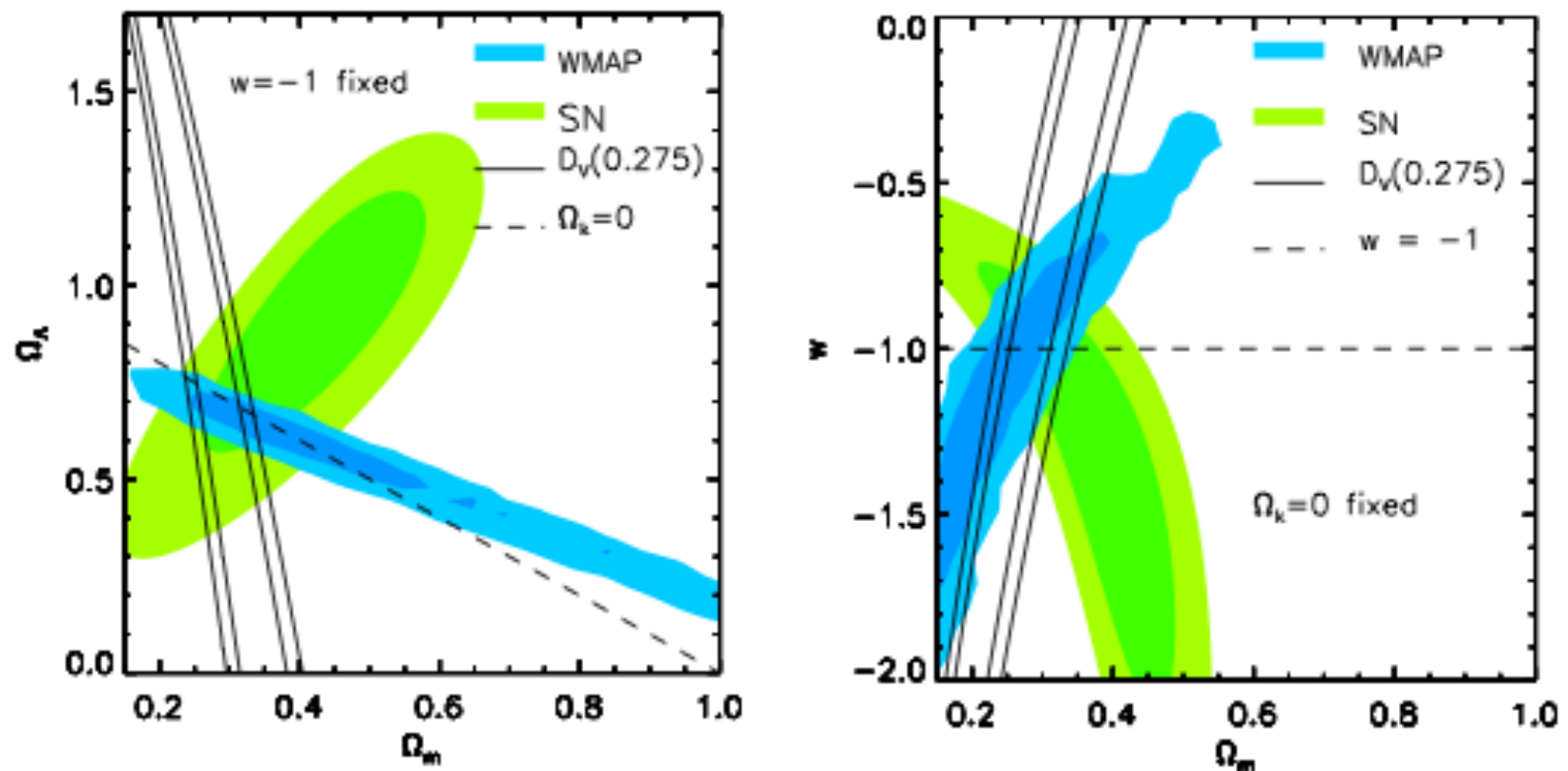
Current combined constraints



Percival et al. (2009)

... on cosmological parameters

Constraints on cosmological parameters from the distance to $z=0.275$.



From Percival et al. (2009); Reid et al. (2009)

The next step?

- We need a much more precise measurement of s at more redshifts to constrain DE.
- To measure $P(k)$ or $\xi(r)$ well enough to see such subtle features requires many well defined modes
 - a Gpc^3 volume.
 - Million(s) of galaxies.
 - Systematic errors need to be controlled to high precision.

The next generation

- There are now proposals for several next-generation BAO surveys, both spectroscopic and photometric.
 - Photometric surveys generally deeper and wider.
 - Not a requirements driver if already doing weak lensing.
 - More susceptible to systematic errors in z determination.
 - Generally takes 3-10x as much sky for same constraints as a spectro survey (# modes in 2D vs 3D).
 - Cannot make use of “reconstruction”.
- Future surveys should be able to measure d_A and H to $\sim 1\%$, giving competitive constraints on DE
- Highly complementary to SNe surveys
 - Completes distance triangle, constrains Ω_K .
 - Locks SNe to absolute distance scale to CMB (in Mpc): h to $\sim 1\%$.

The landscape

- It's difficult to do BAO at very low z , because you can't get enough volume.
- BAO surveys “turn on” around $z \sim 0.3$ and can go as high as $z \sim 3$.
- A point at high z constrains Ω_K
 - Allowing focus on w_0 and w_a at lower z .
- Lower z very complementary to SNe.
 - Completes distance triangle, constrains curvature.
 - Ground BAO+Stage IV SNe (opt), FoM $\uparrow \sim 6x$.
- Tests of GR?
 - Can do lensing from BAO, but weak constraint.
 - Assuming GR, distances give $\delta(z \sim 1)/\delta(z \sim 10^3)$ to $< 1\%$.
 - A spectroscopic survey that does BAO can use redshift space distortions to measure the temporal metric perturbations (c.f. WL which measures sum of temporal and spatial) and hence constrain $dD/d\ln(a)$.

Not-so-next-generation surveys

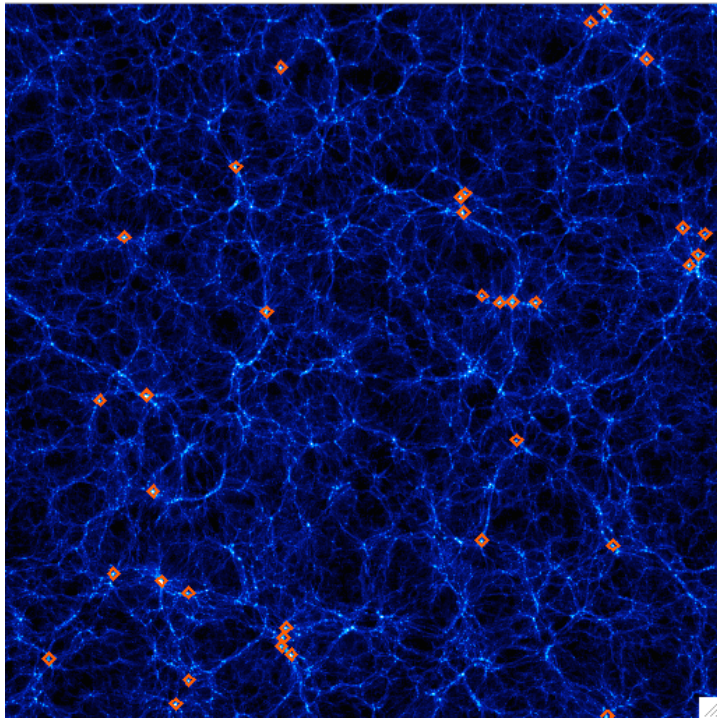
The final round of data (DR7) from SDSS-I & II has been analyzed -- the “next” generation of surveys is underway.

Project	Redshift	Area (sq. deg.)	n (10 ⁻⁴)
WiggleZ	0.4-1.0	1,000	3.0
HETDEX	2.0-4.0	350	3.6
SDSS-III (BOSS)	0.1-0.8	10,000	3.0
	+ 2.0-3.0	+ 8,000	
Pan-STARRS*	0-1	20,000	10

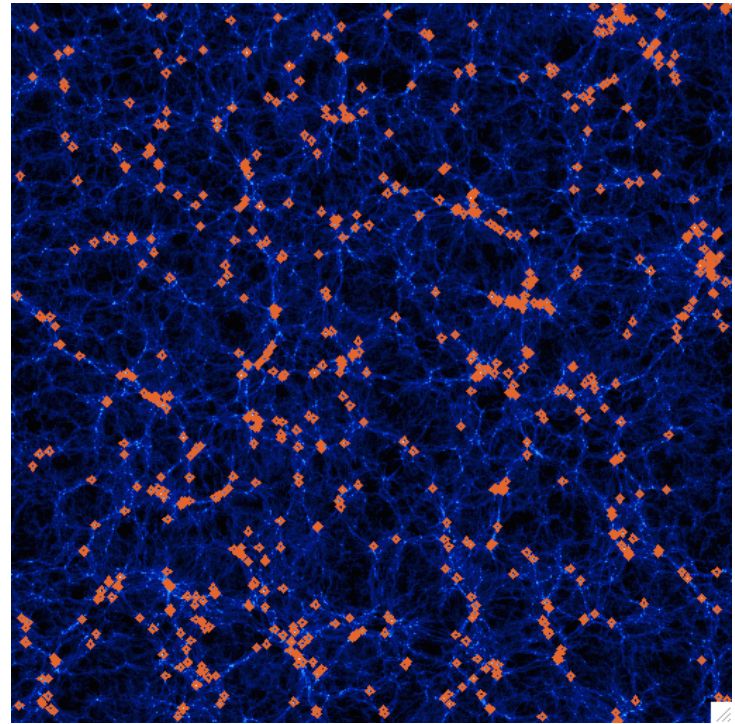
With more waiting in the wings ...

Tracing large-scale structure

The cosmic web at $z \sim 0.5$, as traced by
luminous red galaxies



SDSS

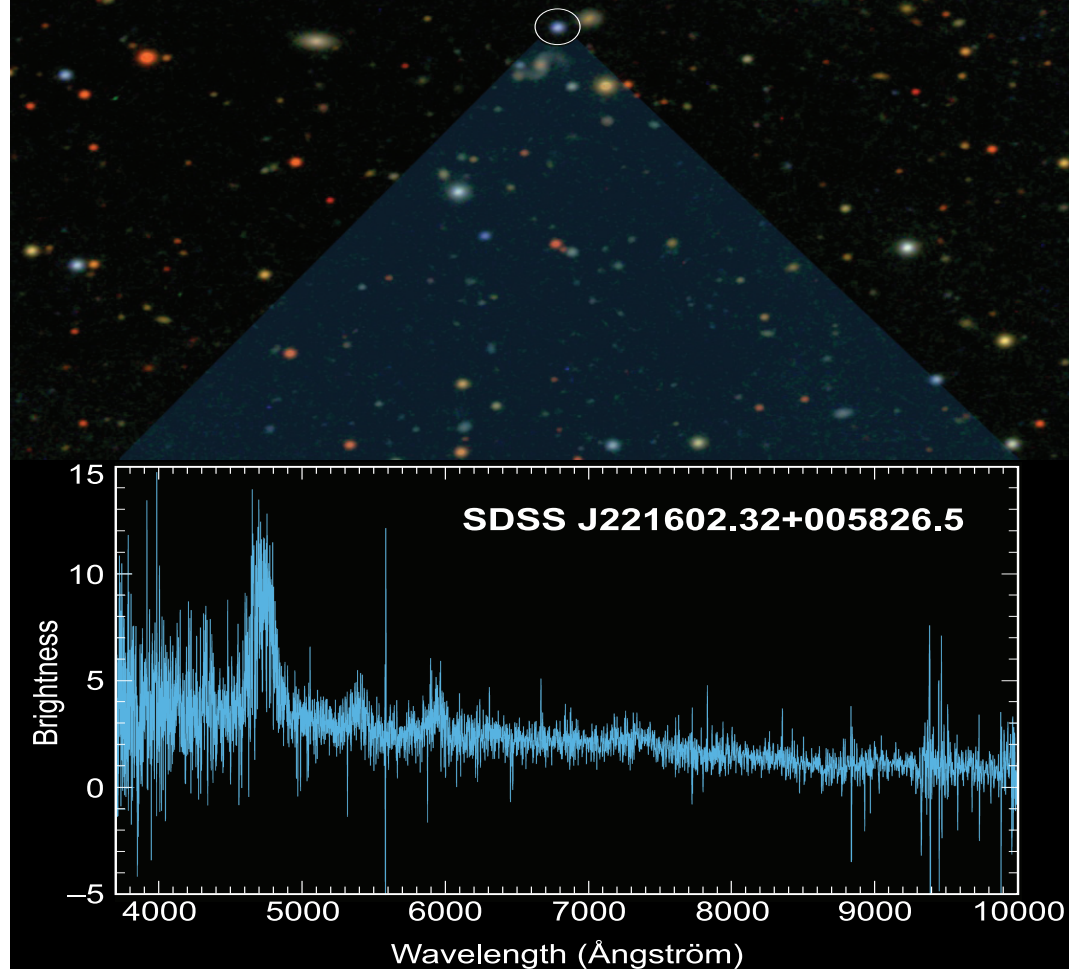


BOSS

A slice $500h^{-1}$ Mpc across and $10 h^{-1}$ Mpc thick

SDSS-III Baryon Oscillation Spectroscopic Survey

D.W. Hogg and V. Bhardwaj for the BOSS team



The upgraded BOSS spectrographs achieved 1st light in Sep. 2009 and BOSS is currently taking data.

Spectroscopy will continue through 2014 with regular data releases to the public (starting in 2012).

BOSS science

Like SDSS-I and II, BOSS will provide a rich scientific return including:

- DE constraints
- A 1% H_0 measurement
- A 0.2% Ω_K measurement
- Strong constraints on primordial non-Gaussianity ($f_{NL} \sim 10$)
- Large scale structure constraints (250,000 modes at $k < 0.2$)
- A S/N=200 measurement of ξ_{gm} from galaxy-galaxy lensing
- Percent level constraints on growth from redshift space distortions
- Constraints on galaxy formation: evolution of massive galaxies
- QSO science (piggy-back program approx. doubles N_{QSO} with $z > 3.6$)
- Galactic structure (C stars)
- Loads of other stuff ...

Findings of the Dark Energy Task Force

(Reporting to DOE, NASA & NSF; chair Rocky Kolb)

- Four observational techniques for studying DE with baryon oscillations:
- “Less affected by astrophysical uncertainties than other techniques.”
- **BUT**
- “We need...Theoretical investigations of how far into the non-linear regime the data can be modeled with sufficient reliability and further understanding of galaxy bias on the galaxy power spectrum.”

Those pesky details ...

- I have argued (convincingly?) that we understand and can calculate the real space, linear theory, matter power spectrum with exquisite accuracy and that it contains highly useful features for cosmology.
- Unfortunately we don't measure the linear theory matter power spectrum in real space.
- We measure:
 - the non-linear
 - galaxy power spectrum
 - in redshift space
- How do we handle this?

Recent BAO “theory”

With the basic measurement demonstrated/validated, theoretical attention has been divided into four areas

1. Understanding the effects of non-linearity, bias & redshift space distortions.
2. Understanding how to perform “reconstruction”.
3. Studying BAO in the IGM.
4. Looking at statistical estimators, covariance matrices, etc.

Numerical simulations

- Our ability to simulate structure formation has increased tremendously in the last decade.
- Simulating the dark matter for BAO:
 - Meiksin, White & Peacock (1999)
 - 10^6 particles, 10^2 dynamic range, $\sim 1\text{Gpc}^3$
 - Springel et al. (2005)
 - 10^{10} particles, 10^4 dynamic range, 0.1Gpc^3
- Our understanding of -- or at least our ability to describe -- galaxy formation has also increased dramatically.

Effects of non-linearity: mass

As large-scale structure grows, neighboring objects “pull” on the baryon shell around any point. This causes a broadening of the peak and additional non-linear power on small scales. From simulations or PT (of various flavors) one finds:

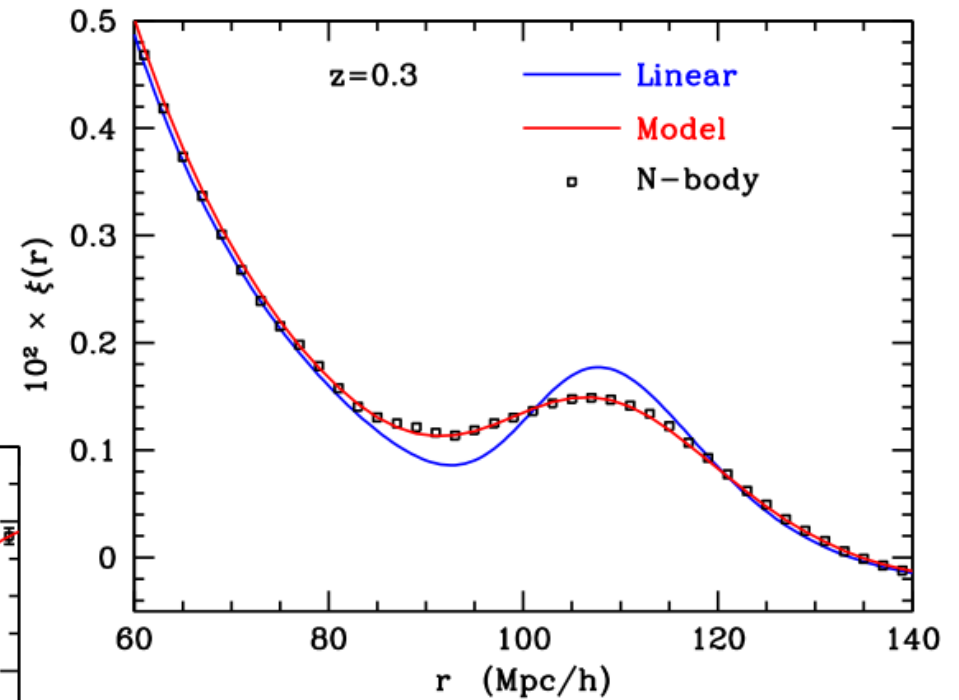
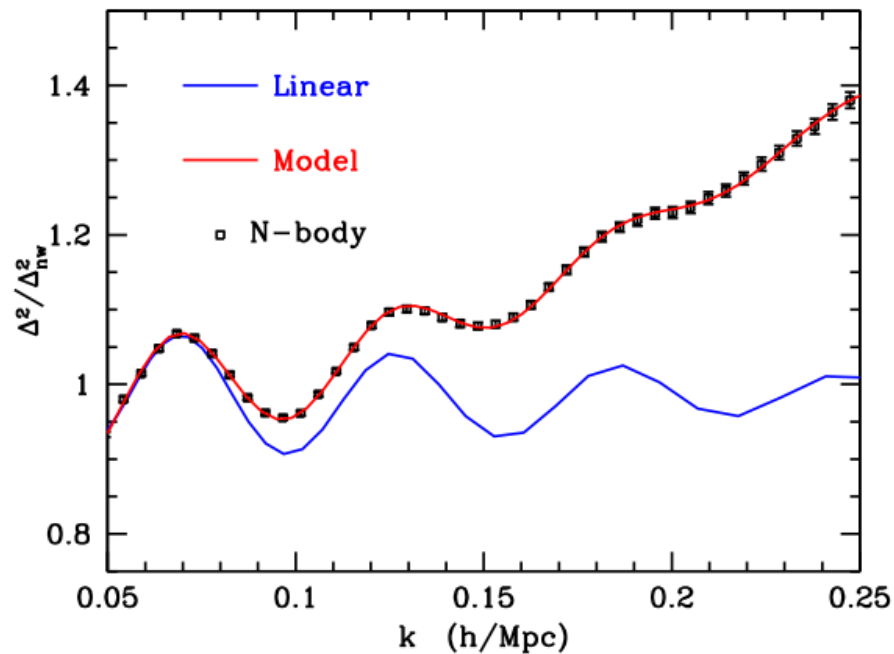
$$\Delta^2(k) = \{ \Delta_{\text{lin}}^2(k) + \cdots \} \exp \left[-k^2 \Sigma^2 / 2 \right] + \Delta_{22}^2 + \cdots$$

This does a reasonable job of providing a “template” low- z spectrum, and it allows us to understand where the information lives in Fourier space [forecasting].

Bharadwaj (1996); Eisenstein, Seo & White (2007); Smith, Scoccimarro & Sheth (2007); Eisenstein et al. (2007); Matsubara (2007); Padmanabhan, White & Cohn (2009); Padmanabhan & White (2009); Seo et al. (2009); Noh et al. (2009); Mehta et al. (2010); ...

Non-linearities smear the peak

Loss of contrast and excess power from non-linear collapse.



Broadening of feature due to Gaussian smoothing and $\sim 0.5\%$ shift due to mode coupling.

Non-linearity II

Both the damping and the “shift” are easy to understand.

- The smearing comes from the displacement of particles from their initial conditions due to gravitational “tugs” of large-scale structure.

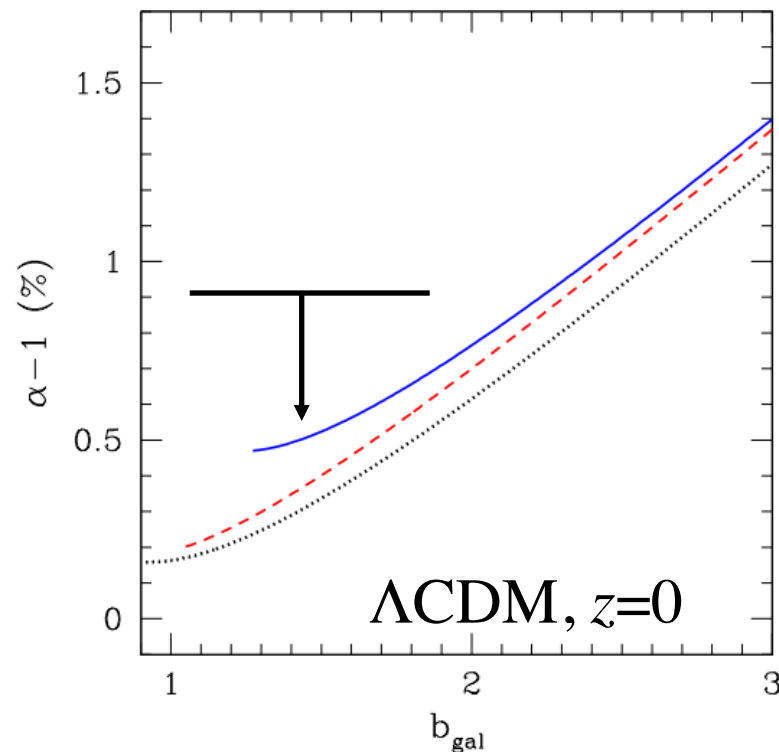
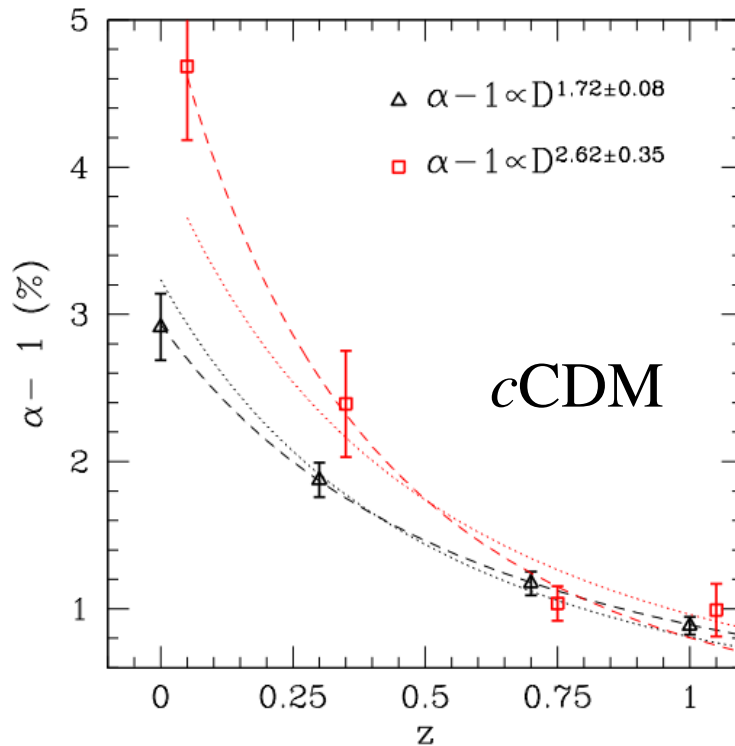
$$\text{Zel'dovich : } \mathbf{s}_k = \frac{i\mathbf{k}}{k^2} \delta_k \quad \Rightarrow \quad \Sigma^2 \propto \langle \mathbf{s}^2 \rangle \propto \int dk P(k)$$

- In pert. theory the full $P(k)$ has terms
 - $P_{\text{NL}} \sim P_L + P_L \int P_L K_1 + \int P_L P_L K_2 + \dots$
- The term $P_L \int P_L$ is benign, but the $\int P_L P_L$ term contains an out-of-phase oscillation
 - $P_L \sim \dots + \sin(kr)$: $P_L P_L K_2 \sim \sin^2(kr/2) \sim 1 + \cos(kr)$
- Since $\cos(x) \sim d/dx \sin(x)$ this gives a “shift” in the peak
 - $P(k/\alpha) \sim P(k) - (\alpha-1) dP/d\ln k + \dots$

Bias & redshift space

- If one goes into redshift space, or uses biased tracers, then many more terms come in - but they all have the same basic form.
- This intuition can be explicitly tested on numerical simulations.

Padmanabhan & White (2009)

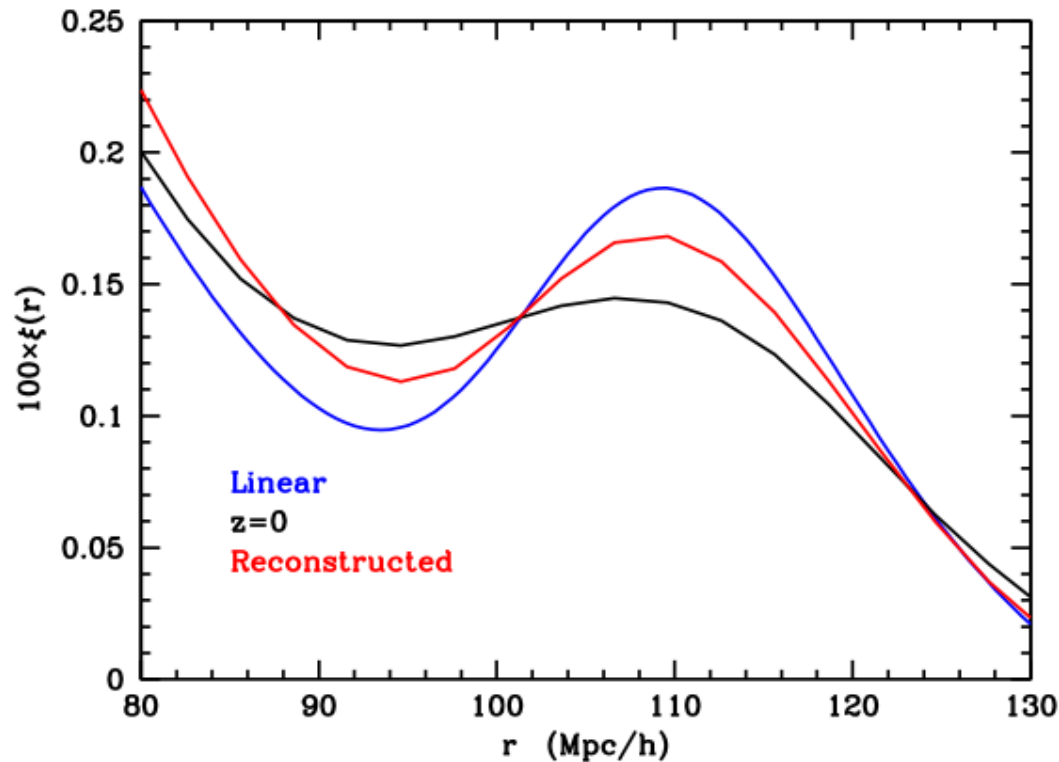


Reconstruction

- The broadening of the peak comes from the “tugging” of large-scale structure on the baryon “shell”.
- We measure the large-scale structure and hence the gravity that “tugged”.
- Half of the displacement in the shell comes from “tugs” on scales $> 100 \text{ Mpc}/h$
- Use the observations to “undo” non-linearity (Eisenstein++07)
 - Measure $\delta(x)$, infer $\phi(x)$, hence displacement.
 - Move the galaxies back to their original positions.
- Putting information from the phases back into $P(k)$.
- There were many ideas about this for measuring velocities in the 80’s and 90’s; but not much of it has been revisited for reconstruction (yet).

Eisenstein++07; Huff++07; Seo et al.++08,09;
Wagner++08; Padmanabhan++09; Mehta++09;
Noh++09; ...

Reconstruction



Reconstruction helps to sharpen the peak in the correlation function which is smeared by non-linear evolution.

This seems relatively “easy”, **BUT**, to date reconstruction hasn’t been demonstrated on non-simulated data.

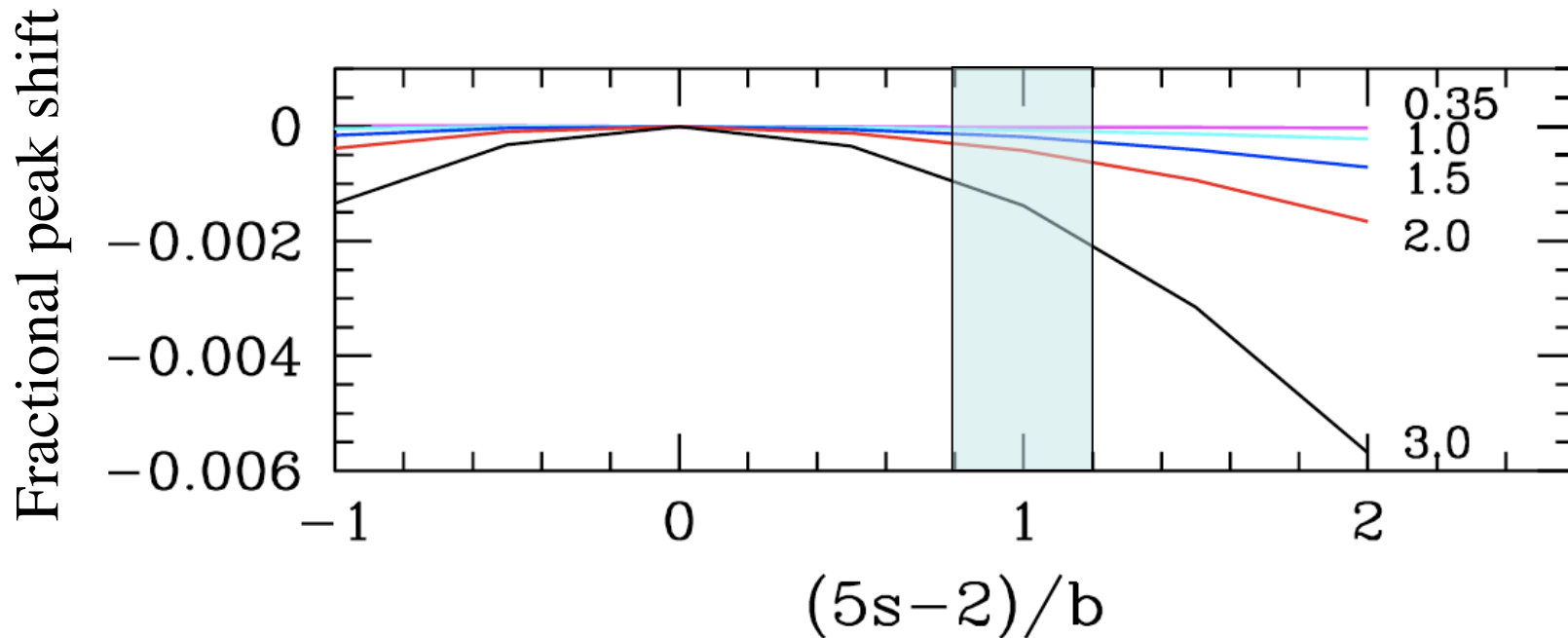
Lensing

Hui, Gaztanaga & LoVerde: effects of lensing on the correlation function.

For next-generation experiments effect is small.

Eventually may be measurable: template known.

$$\xi_{obs}(R, z) = \xi \left(\sqrt{R^2 + z^2} \right) + f(R)z + g(R)$$

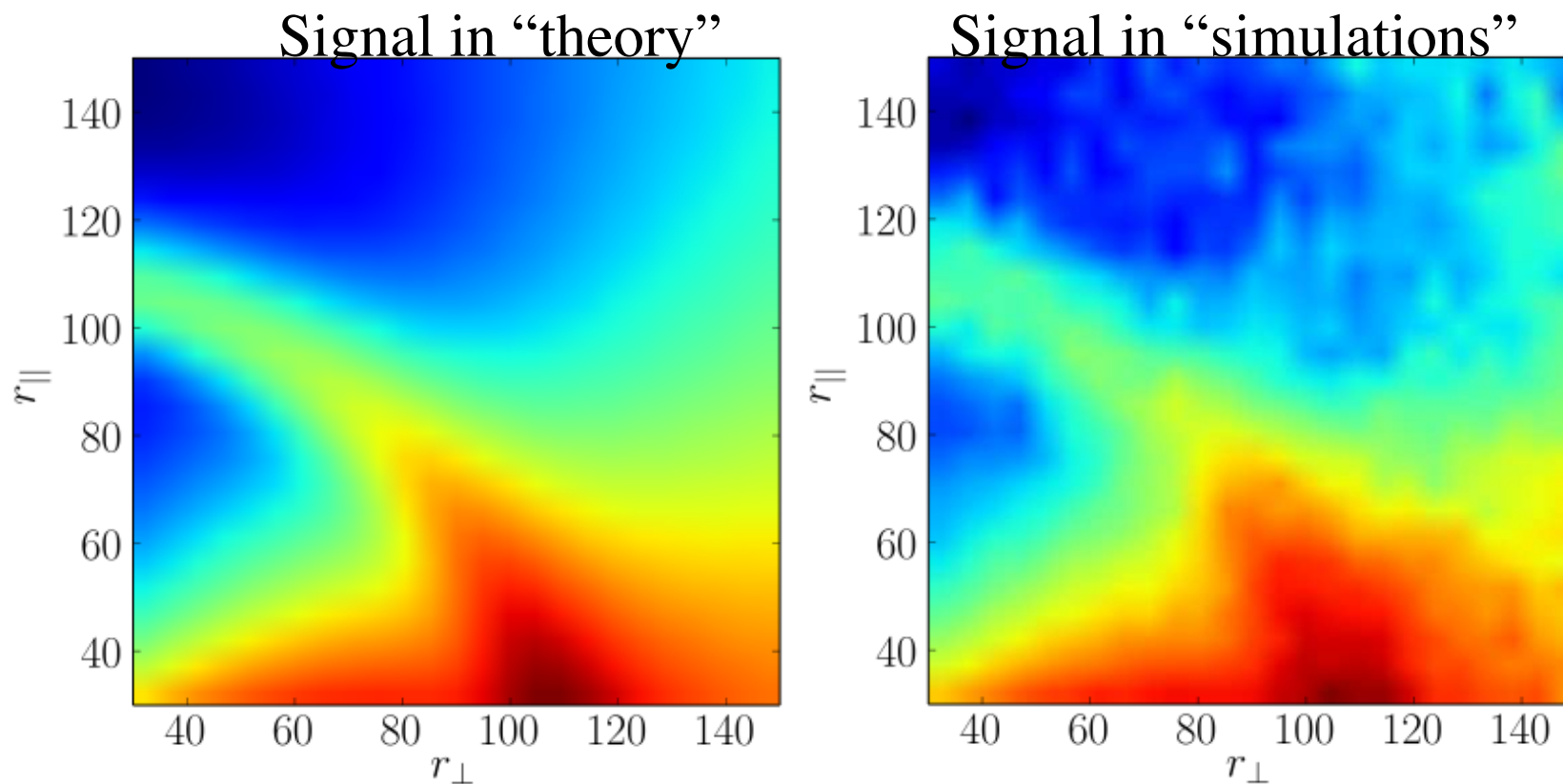


BAO and the IGM

- Distance constraints become tighter as one moves to higher z
 - More volume per sky area.
 - Less non-linearity.
- Expensive if use galaxies as tracers.
- Any tracer will do: HI
 - 21cm from HI in galaxies: SKA or custom expt.
 - Ly α from IGM as probed by QSOs.
 - If IGM is in photo-ionization equilibrium
 - Absorption traces mass in a calculable way.
 - $\text{Flux}(\lambda) \sim \exp[-A(1+\delta)^\beta]$ (Cen++94, Hui & Gnedin 97, Croft++98)
 - A dense grid of QSO sightlines could probe BAO
 - (White 2003, McDonald & Eisenstein 2007, Slosar++09, White++10)
- e.g. 8,000 deg² to $g \sim 22$ gives 1.5% (d_A & H)
 - Comparable to other forecasts but with a 2.5m telescope!

BAO at high z

Slosar, Ho, White & Louis (2009)



BAO feature survives in the LyA flux correlation function, because on large scales flux traces density.
Relatively insensitive to astrophysical effects.

Ongoing work

- Templates for fitting data, able to account for non-linearity, redshift space distortions and galaxy bias.
- New estimators optimized for large-scale signals calibrated by numerical simulations.
- Models for the covariance matrices, calibrated by simulations.
- More sophisticated reconstruction algorithms.
- Some “new” ideas, and experimental approaches ...

Conclusions

- Baryon oscillations are a firm prediction of CDM models.
- Method is “simple” geometry, with few systematics.
- The acoustic signature has been detected in the SDSS!
- With enough samples of the density field, we can measure $d_A(z)$ and $H^{-1}(z)$ to the percent level and thus constrain DE.
 - Was Einstein right?
- Require “only” a large redshift survey - we have >20 years of experience with redshift surveys.
- Exciting possibility of doing high z portion with QSO absorption lines, rather than galaxies.
- It may be possible to “undo” non-linearity.
- Understanding structure and galaxy formation to the level required to maximize our return on investment will be an exciting and difficult challenge for theorists!

The End